A G-APD based Camera for Imaging Atmospheric Cherenkov Telescopes

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Abstract

Imaging Atmospheric Cherenkov Telescopes (IACT) for Gamma-ray astronomy are presently using photomultiplier tubes as photo sensors. Geiger-mode avalanche photodiodes (G-APD) promise an improvement in sensitivity and, important for this application, ease of construction, operation and ruggedness. G-APDs have proven many of their features in the laboratory, but a qualified assessment of their performance in an IACT camera is best undertaken with a prototype camera. This paper describes the design and construction of a full-scale camera based on G-APDs undertaken within the FACT project (First G-APD Cherenkov Telescope).

Key words: Geiger-mode avalanche photodiode, Cherenkov telescope, extensive air shower, gamma-ray astronomy
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1. Introduction

Gamma-ray astronomy addresses highly energetic processes in the universe through measurements of high-energy photons that travel through space undeflected by magnetic fields and are only weakly absorbed by the interstellar and intergalactic medium [1].

Photons from space with a wavelength shorter than ultraviolet are fully absorbed in the atmosphere, thus direct detection is possible only in space or with high-altitude balloons. The high launch costs limit the affordable detector sizes, and, due to the steeply falling source intensities with energy, the attainable spectral reach. As an example, from one of the strongest sources of gamma rays, the Crab nebula, a flux of about 0.2 photons/cm^2/year is received above 50 GeV.

The absorption of high-energy cosmic rays or photons by the atmosphere results in air showers. Detection is possible either through the particle content of the shower, for example with extensive arrays of scintillators, or through radiation generated by the shower in the atmosphere. This can be in the form of fluorescence, radio emission, or, as used by the detection technique described here, Cherenkov light.[4]

The Cherenkov technique for gamma-ray astronomy has been developed relatively recently. The first Cherenkov light pulses from the atmosphere were detected in 1952 [2], four years after a prediction that this should be possible. The first clear observation of gamma-induced showers from a cosmic source, however, was achieved only in 1989 by the Whipple telescope [3]. It required the establishment of the imaging technique and substantial work on simulations to eventually achieve an undisputed detection.

The main challenge with Imaging Atmospheric Cherenkov Telescopes (IACT) is the discrimination against background. Hadronic showers, e.g., are orders of magnitude more frequent than gamma-induced showers. The discrimination power of an IACT results from the relatively clear difference in appearance of air showers induced by hadrons and photons when imaged with a telescope onto a pixelized camera. The gamma-ray energy can be reconstructed to about 15% at energies of several 100 GeV for large telescopes, the arrival direction (source location) to a few minutes of arc. Both limits result from the basic statistical uncertainty of the shower development. This permits to use mirrors of moderate surface accuracy (when compared to astronomical optical telescopes) and also relatively large camera pixels.

One important direction of development in the field is the reduction of the energy threshold. If an overlap with testbeam-calibrated space detectors can be achieved (especially with the Fermi satellite), cross-calibration will be possible.

2. Geiger-mode Avalanche Photo Diodes

The newly developed Geiger-mode Avalanche Photo Diodes (G-APD) have several significant advantages compared to photomultipliers for the application in IACTs. Both the peak and

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[4] This is in essence a calorimetric technique, with a fully active absorbing medium. Note that the atmosphere is 27 radiation length deep.

spectrally averaged photon detection efficiencies are higher, helping in decreasing the energy threshold. Their angular response is uniform up to high inclinations, thus allowing to use non-imaging light concentrators with a high cross-section reduction.[5] They tolerate background light, which translates to an extension of the measurement time into the twilight and into moon-lit nights. Mechanically they are rugged, and they need only a low bias voltage of around 70 V.

Their main disadvantage is the strong dependence of gain on temperature. Controlling this in an IACT that is inevitably coupled to ambient temperature to some degree is one of the main challenges that has to be addressed. Another disadvantage is the relatively long signal decay time constant in view of the presence of counts induced by background light at rates up to several GHz and the resulting pile-up.

Another issue is optical cross-talk that results in firing of additional cells. This cross-talk prevents further increase of the photon detection efficiency by operating at higher bias voltage that would, in turn, increase the avalanche probability. Also, up to now no long term experience with G-APDs on an IACT exists.

The non-linear response of G-APDs once a significant fraction of cells fired is less important for the IACT application. It actually gives some desirable signal compression at the high energy end.

3. Test module M0

To gain first practical experience with a G-APD based camera, a small test module, called M0, has been constructed . It has 36 pixels, each consisting of four Hamamatsu S10362-33C-050C G-APDs that are analog summed. The module is mounted in the focal plane of a small zenith-looking Cherenkov telescope, located at ETH Zürich, to record light from Cherenkov showers. Sub-nanosecond time resolution has been achieved with the Domino Ring Sampling chip DRS2 [4], operated at 2 GHz sampling, as primary data acquisition element. Using a majority-coincidence trigger, cosmic-ray induced air showers with clear time and intensity signatures have been recorded. The design and first results are published in [5]. This test confirmed that it is possible to observe Cherenkov light from air showers with G-APDs. M0 is used continuously for testing new components and software during development of the full scale camera.

4. Studies on G-APD gain control

Studies to mitigate the main G-APD disadvantage, the strong gain dependence on temperature, have been undertaken with M0 as well. A feedback that regulates the bias voltage has been implemented for this purpose. Pulses from intensity-stabilized blue-emitting LEDs illuminate the sensors indirectly through small scattering centers machined into the entrance window.

[5] Since light is not compressible in phase space, such a concentrator trades cross-section for angular dispersion.

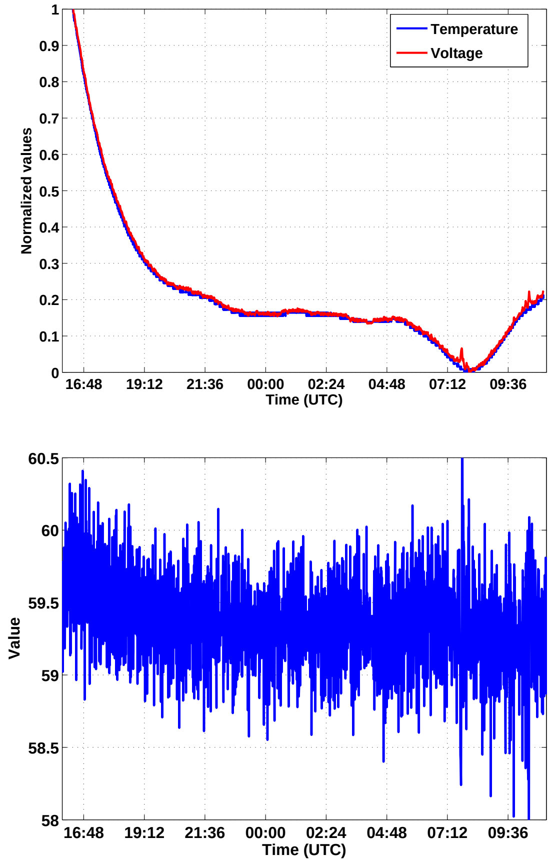

Figure 1: Test results of the bias feedback. Temperature and the feedback-regulated voltage (top), linearly mapped to the range 0 to 1, and the feedback signal for the same period (bottom).

The data acquisition system extracts those events that result from an LED pulse and integrates the signal over the light pulse duration of about 50 ns. An average of these values over a given number of events is then calculated (this is called the feedback signal). Typically 500 events are averaged, and the LEDs are pulsed at a rate of about 10 Hz.

As first step in establishing the regulation, the G-APD voltages have to be manually set to the correct values for the current temperatures. The feedback signals are recorded as target values. The bias voltages are then changed by about 500 mV, and new feedback signals are acquired. From the difference, the response values needed for regulation are determined.

After activation, the feedback will adjust the bias voltages to keep the feedback signals stable. The feedback gain with the current M0 electronics is set typically between 0.2 and 0.5.[6]

The behaviour of the feedback is illustrated in Fig. 1. The test module was operated overnight, with shutter closed, and without active cooling. The temperatures in the camera were thus following ambient conditions. The top figure shows the temperature and voltage, as regulated by the feedback, both mapped

[6] The gain is the fraction of the nominal voltage step, required to bring the signal to exactly its target value, that is actually applied. The optimum value depends on the measurement noise and the desired regulation speed.

linearly to the range 0 to 1. Both traces lie on top of each other in this representation. This is expected since the overvoltage has a linear dependence on the temperature for fixed gain. The feedback signal for the same measurement period is shown in the lower plot. It is stable to better than 1%, the fluctuations coming mostly from measurement noise. Some contribution to the noise also comes from the feedback itself, and is currently the target of optimization of the feedback parameters.

In actual numbers, the temperature decreased from 12.6°C to 5.0°C, and the voltage from 70.55 V to 70.05 V. Without voltage regulation, the feedback signal would have changed by about 50% due to the temperature change.[7] This demonstrates how well the strong gain dependence on temperature of the G-APD sensor can be compensated with a simple feedback. Several qualitative tests have been performed in the presence of night sky background (shutter open), indicating that the feedback regulation works also in such conditions.[8] Detailed studies are deferred until the final electronics and light pulser are available.

An attractive feature of this method is that it stabilizes the signal without knowledge of an actual temperature or of the background rate. However, since the rate of LED events is limited due to the maximum data throughput and implied penalty of dead time, the regulation speed is also limited and thus some direct stabilization of temperature is still desirable. The effect can be seen in Fig. 1 by the slight drift of the feedback signal when the temperature changes rapidly (about 0.1 K per minute on the steep slope around 17:00).

The good separation of signals that result from only a few fired G-APD cells allows also an absolute gain determination. Fig. 2 shows a signal histogram, obtained by applying a simple peak-finding algorithm to data containing only dark counts[9]. An additional analog gain of 9 was used for this measurement to compensate for the limited resolution of the preamplifier and DRS2. Due to cross-talk, a dark count spectrum contains signals with more than one fired cell, as can be seen from the multiple-Gaussian fit. The position of the first maximum above pedestal, or the difference between first and second, gives the G-APD gain. Although tracing the gain will not be possible in the presence of intense night sky background, as pile-up will prevent signal extraction with sufficient precision, the method is useful for verifying the sensor operation with closed shutter.

5. FACT

Although the experience with the test module M0 clearly indicates the feasibility of a G-APD based Cherenkov camera, a full assessment of the technology implications can only be undertaken with a full scale device [6]. In particular, the test module did not allow to investigate the crucial step of gamma/hadron separation due to its small number of pixels.

The full-scale FACT camera will contain 1440 pixels, each with a field-of-view of 0.11°. Each pixel will consist of one G-APD of the same type as used for M0, glued to one solid cone light concentrator [7]. The total field-of-view will be 4.5°. Entrance window and light concentrators will be fabricated from polymethyl methacrylate (PMMA) with enhanced ultraviolet transmission. The mechanical layout of the camera is shown in Fig. 3.

Signal digitization and the trigger logic will be integrated into the camera, with digital data transferred via Ethernet carried over optical fibers to a central event builder. Bias voltages will be fed in from an external, USB-controlled source.

The basic internal camera structure consists of two thermally separated compartments, one containing the light sensors, the other the read-out electronics, arranged in four individual crates. The total power consumption of the electronics is around 1 kW, therefore the crates are individually cooled to reduce thermal impact on the sensor compartment.

The G-APD gain will be stabilized to about 5%. A detailed thermal design is currently developed together with an industrial partner, and a bias voltage feedback along the same principles as described in Sect. 4 will be used. A faster (subnanosecond), monitored light pulser is foreseen to increase the stability and regulation precision.

The camera will be installed in fall 2010 on the former 4 m diameter HEGRA CT3 telescope, refurbished with new mirrors and a new drive system. The site is next to the MAGIC telescopes on La Palma, Canary Islands, which will allow simultaneous observations and in turn faster commissioning of FACT. After commissioning and detailed studies on this novel technology, the camera will be used for routine and long-term monitoring of selected strong, variable gamma-ray sources.

Details of the electronics can be inferred from the block diagram in Fig. 4. The next version of the DRS analog pipeline chip, DRS4, will be used for digitization [8], giving a signifi-

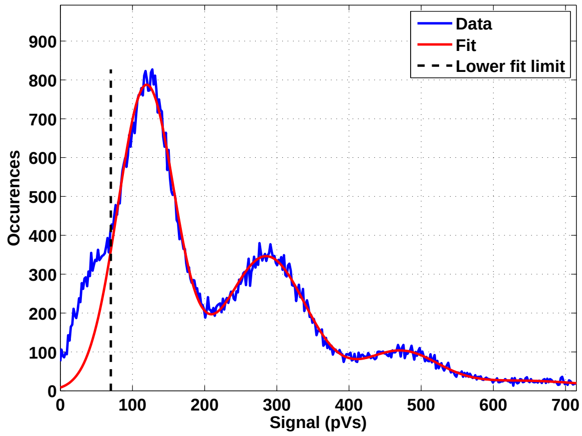

Figure 2: Amplitude histogram of dark counts. Extraction by a peak-finder algorithm from signals digitized at 2 GHz with the DRS2. The G-APD is at room temperature. A multiple Gaussian fit is used.

[7]For the used G-APD, the gain changes by 1% per 0.2 K at the nominal operating point.

[8]An increased background rate will decrease the actual G-APD voltage through an increased voltage drop across the decoupling resistors, and thus decrease the gain and the signal. It will also increase the mean occupancy of the G-APD.

[9]With shutter closed, the G-APDs of M0 generate dark counts of about 5 MHz rate at room temperature.

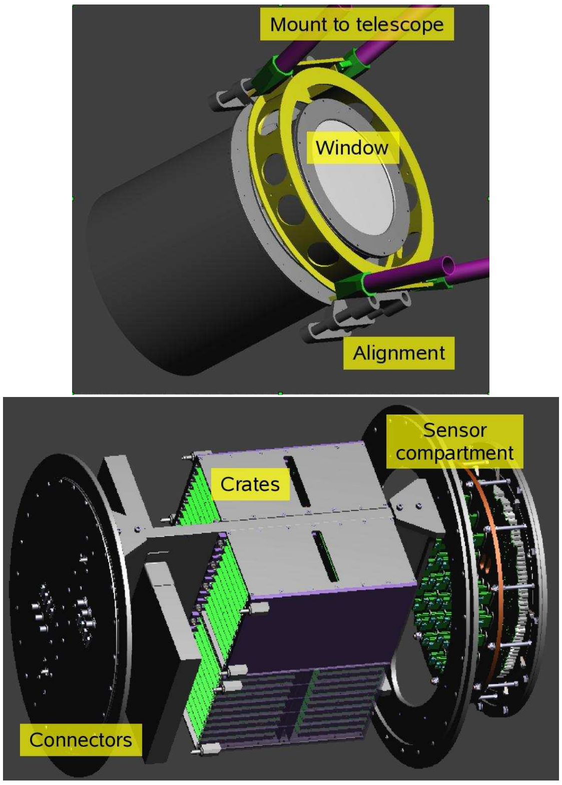

Figure 3: Mechanical design of the FACT camera. The length is about 800 mm, the diameter 530 mm. The sensor compartment, located behind the window, is thermally separated by a copper plane from the electronics.

cantly increased resolution. We measured a baseline noise of 310 µV, with a dynamic range up to 1 V, and a timing resolution of 110 ps at 2 GHz sampling. Both figures are adequate for our application.

For triggering, nine analog G-APD signals will first be summed, then discriminated, and the result fed into a majority logic. Non-overlapping trigger patches will be used for simplicity in the first version of the camera, with the possibility to upgrade the trigger system later.

Slow control within the camera, for example for threshold adjustment commands from the trigger master to the individual trigger boards as shown in Fig. 4, is based on RS-485 connections. Unique event IDs, distributed to the digitizers also via RS-485, will be included in the TCP/IP packets that are send to the event builder in the counting house.

The nominal trigger rate is 150 Hz, resulting in a data rate of 41 MByte/sec if 10% of the analog pipeline (corresponding to about 50 ns) is read-out. The throughput from the camera to the event builder will, however, be designed for significantly higher data rates, to allow the future implementation of a second-level software trigger.

The control system of FACT is based on the DIM interprocess communication system developed at CERN [9]. DIM interconnects individual servers, each controlling one system component, via TCP/IP. The control system consists of the slow data acquisition system, a central configuration server, and an alarm server monitoring system health. A fully separated graphical user interface is implemented within the Qt framework.[10] Data analysis will be based on established tools also used by the MAGIC collaboration [10].[11] The overall layout of the control system is geared towards later automatic operation, with only occasional remote surveillance.

6. Conclusion

The feasibility of a G-APD camera has been proven by detecting light from Cherenkov showers with the test module M0.

The full-scale FACT camera will start taking data in fall 2010, initially by observing the Crab nebula. It will be mounted on the refurbished HEGRA CT3 telescope. The first goal is a realistic performance evaluation of the G-APD based camera for the IACT application. After the commissioning is finished, the telescope will be used for monitoring selected, strong and variable gamma-ray sources.

FACT will be an important step in establishing G-APDs as an option for the next generation of large Cherenkov telescopes (AGIS/CTA).

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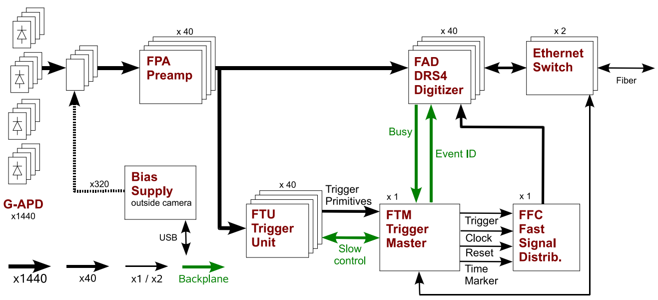

Figure 4: Block diagram of the FACT camera. Fast signals are distributed by cables, slower ones over the central backplane in each crate.

[10] Free at http://qt.nokia.com/products/ for non-commercial applications.

[11] Further information also at http://wwwmagic.mppmu.mpg.de/.